NOAA's CoastWatch: Satellite Environmental Monitoring of the Great Lakes*

G.A. Leshkevich, D.J. Schwab and G.C. Muhr
NOAA Great Lakes Environmental Research Laboratory
Ann Arbor, Michigan USA

ABSTRACT

To address critical coastal environmental problems, the National Oceanic and Atmospheric Administration (NOAA) has established the Coastal Ocean Program. Within that program, CoastWatch is designed to provide a rapid supply of up-to-date, coordinated, environmental information, including remotely sensed data, to support Federal and state decision makers and researchers who are responsible for managing the Nation's living marine resources and ecosystems. This paper describes the NOAA CoastWatch program for the Great Lakes. The initial products of the CoastWatch program, a set of surface water temperature images, are routinely derived from NOAA AVHRR (Advanced Very High Resolution Radiometer) satellite data and made available within hours of acquisition. Preliminary analysis has shown excellent correlation of satellite-derived temperatures with in situ water temperature measurements from mid-lake weather buoys. Other products including turbidity, ocean color, and ice mapping are planned. Components of the CoastWatch system including a wide area communications system, on-line product data bases, an electronically-accessible product archive, and PC software for display and analysis of the satellite imagery are also described.

1.0 INTRODUCTION

In response to an occurrence of "Red Tide" off the coast of North Carolina in late1987, a program was developed by NOAA's National Environmental Satellite and Data Information Service (NESDIS) to provide the NOAA National Marine Fisheries Service Laboratory at Beaufort, North Carolina with satellite-derived sea surface temperature (SST) maps of the Gulf Stream and other types of data so that future occurrences of this phenomenon or other coastal environmental events could be better anticipated and monitored (Pyke, 1989). This program has since been extended to other coastal regions in the United States, including the Great Lakes, and has been expanded to become the CoastWatch program, a part of NOAA's Coastal Ocean Program. The goal of theCoastWatch program is to develop and deliver environmental data and products for near real-time monitoring of U.S. coastal waters to support environmental science and decision making. The objectives of CoastWatch are: 1) to provide access to near real-time and retrospective satellite and aircraft observations of the U.S. coastal ocean for Federal, state, and local decision making, 2) to develop workstations and associated software systems for integrated analyses of environmental quality, coastal hazards, and wetlands change, 3) to develop a communications system supporting distribution of near real-time and historical satellite and in situ observations to national and regional coastal users, and 4) to develop and implement a data base management and display system

----

*Presented at the First Thematic Conference on Remote Sensing for Marine and Coastal Environments, New Orleans, Louisiana, USA, 15-17 June 1992.

supporting integrated coastal ocean applications. NOAA CoastWatch directly supports agency statutory responsibilities in estuarine and marine science, living marine resource protection, and ecosystem monitoring and management contained in several Federal environmental statutes including the U.S.-Canadian Great Lakes Water Quality Agreement.

In 1990, as part of the CoastWatch program, NOAA's Great Lakes Environmental Research Laboratory (GLERL) located in Ann Arbor, Michigan was chosen as the CoastWatch Regional Site for the Great Lakes. The initial CoastWatch product for the Great Lakes was digital imagery of lake surface temperature at resolutions of 1.3 and 2.6 km, derived from NOAA satellite data. Mapped to a Mercator projection, several of these images per day have been received at GLERL electronically via the NOAA Ocean Communications Network (NOCN) since April 1990. In addition, in situ and modeled data products currently being received include Marine Observation Data and Fields of Information by Blending and Smoothing (FIBS) gridded atmospheric pressure and wind field data. Figure 1 summarizes the acquisition of the Great Lakes CoastWatch product suite since April 1990. GLERL will soon be receiving an enhanced daily image product suite of 24 images including surface temperature, visible and near-infrared reflectance, brightness temperatures, and satellite and solar zenith angle data (see Table 1 for description).

As a CoastWatch Regional Site, GLERL will make Great Lakes CoastWatch products available to other regional users including Federal agencies, state and local government agencies, academic institutions, and other organizations engaged in cooperative research programs with NOAA. The first Great Lakes regional user site was established at the Center for Great Lakes Studies at the University of Wisconsin-Milwaukee in 1990. Since then, regional users have grown in number to include 10 active users from Federal and state government agencies and academic institutions.

2.0 DATA / PRODUCTS

Current CoastWatch image products, i.e., water surface temperature imagery and visible (Ch.1) and near-infrared (Ch.2) reflectance data, are obtained from NOAA polar-orbiting weather satellites. There are currently two operational polar-orbiting weather satellites (NOAA 11 and NOAA 12) which each carry (among other sensors) the Advanced Very High Resolution Radiometer (AVHRR). Initial CoastWatch surface temperature imagery received was produced from both NOAA 10 and NOAA 11 data. Although NOAA 12 has recently become operational, current image products are produced from NOAA 11 data. NOAA polar-orbiting satellites are in a sun synchronous orbit at an altitude of approximately 833 km. Each satellite passes over a given area twice a day - about 2 A.M. and 2 P.M. local time for NOAA 11. (The NOAA 10 daytime and nighttime overpasses were at about 7 A.M. and 7 P.M. local time.) The AVHRR scans a swath of approximately 2700 km on the earth's surface beneath the satellite in five radiometric bands, Ch.1 - visible (0.58-0.68 μm), Ch.2 - reflected infrared (0.725-1.0 μm), and three thermal infrared (Ch.3 - 3.55-3.93 μm, Ch.4 - 10.3-11.3 μm, Ch.5 - 11.5-12.5 μm) (Koczor, 1987). AVHRR data are processed at two resolutions, 4 km Global Area Coverage (GAC) and 1 km Local Area Coverage (LAC) and High Resolution Picture Transmission (HRPT). The HRPT data are used for Great Lakes CoastWatch imagery. These data are downloaded to a satellite receiving station then transmitted to NESDIS facilities in Suitland, Maryland where they are calibrated, earth located, quality controlled, and made available as AVHRR level 1b data sets (see Kidwell, 1991 and Pichel et al., 1991 for details of this process). For the CoastWatch program, the level 1b data are mapped to a Mercator projection and resampled to a 512x512 pixel grid. Four scenes or "windows" are extracted for the Great Lakes region as shown in Figure 2 and listed in Table 2. One synoptic scene covers all five lakes at a 2.56 km central resolution. The other three scenes focus on Lake Superior, Lakes Michigan and Huron, and Lakes Erie and Ontario at twice the resolution of the five-lake scene (see Figure 3). Actual grid resolution is determined by d $\cos\phi$ where d is the spatial resolution at the equator, and ϕ is the latitude. The grid spacing for the three high resolution Great Lakes scenes ranges from 1.24 to 1.30 km as indicated in Table 2.

The accuracy of the mapping algorithms used to generate the level 1b data and Mercator projection depends on the precision with which the satellite orbital characteristics are known. Owing to the changing nature of these characteristics for the NOAA weather satellites, the automatically mapped images have usually required adjustments of from 5-10 km to be correctly located with respect to the scene windows in Figure 2.

Possible applications of temperature (and reflectance) imagery to the analysis of lake physics are numerous. Bolgrien and Brooks (1992) describe and illustrate the development of vernal thermal fronts and other thermal features in Lake Michigan using CoastWatch temperature imagery. Schwab et al. (1992) demonstrate the potential utility of CoastWatch temperature imagery for monitoring thermal fronts, analyzing surface circulation patterns, and detecting and mapping ice cover. Turbidity maps can also be derived using the visible and near-infrared imagery.

2.1 SURFACE TEMPERATURE

Surface temperature is calculated for each pixel in the scene (using the equations described below), regardless of whether it is land or water. The mapped surface temperature images are stored in computer files as 11 bit integers and can be converted to temperature as follows:

$$
\begin{array}{lcl}
0 < n \leq 920 & : & SST = 0.10n + 178 \\
920 < n \leq 1720 & : & SST = 270 + 0.05\,(n-920) \\
1720 < n \leq 4095 & : & SST = 310 + 0.10\,(n-1720)
\end{array}
$$

where n is the 11 bit integer and SST is in degrees Kelvin. This mapping provides a 0.05 degree C resolution over the main region of interest for water temperatures. Four bits of graphics information including lake shorelines, state boundries, and a latitude-longitude reference grid are appended to the temperature data. A data compression technique is used to minimize data storage requirements and speed data transmission. The temperature values are stored row by row as 16 bit integers, except where a value is within 63 counts of the previous value, in which case it is stored as an 8-bit integer offset in the range -63 to +63.

2.2 VISIBLE / NEAR INFRARED BANDS

Imagery of visible (Channel 1) and near infrared (Channel 2) reflectance has been received for the Great Lakes synoptic and Lake Michigan windows on a limited basis. When the OCNMAP procedure is implemented (June 1992), this image data as well as satellite and solar zenith angle data will become available on a daily basis (see Table 1). In Figure 4, a NOAA 11, Channel 1 scene acquired on 19 May 1992, areas of higher reflectance are depicted as lighter in tone. Visible and near-infrared reflectance data can be used in mapping Great Lakes ice cover and as input data in the calculation of turbidity.

2.3 MARINE OBSERVATIONS

Marine observations have been acquired by GLERL since August 1987 and are extracted from observational data of the Great Lakes Marine Observation Network, comprised of 285 stations including 14 moored buoys, 168 vessels, 8 CMAN stations, 30 US Coast Guard stations, 10 OMR (Other Marine Reports (wind data only)), 11 surface synoptic stations, and 44 surface airways stations. Frequency of observational reporting ranges from twice per hour to once every 2 hours depending on the type of station. Some surface airways stations report every 30 minutes, while most ships report irregularly. The GLERL data base includes the following information extracted from Great Lakes Marine Observation Network reports: air temperature, dew point, wind direction, wind speed, maximum wind gust, cloud cover, air pressure, water temperature, wave height, and wave period. Most stations usually report selected fields from the above list, with buoys and CMAN stations providing the most complete and reliable data sets. A typical day would include around 180 buoy observations, 1400 observations from land stations, and about 100 reports from vessels.

2.4 GRIDDED WIND FIELDS

GLERL has been receiving objectively analyzed surface wind and atmospheric pressure FIBS fields from the Navy Fleet Numerical Ocean Center (FNOC) via NOCN on a four times per day schedule since November 1990. National Weather Service (NWS) and marine observation data are used to initialize the model which produces surface wind and pressure fields for the Great Lakes at a 30 km grid resolution, as shown in Figure 5. These fields are being used at GLERL to better interpret the CoastWatch temperature imagery and to provide initialization and boundary conditions for model runs and analysis of thermal structure, circulation, storm surges, and wind waves in the Great Lakes.

3.0 SST ALGORITHMS / VERIFICATION

Since 1990, three procedures have been used to create and map Great Lakes surface temperature images: SSTMAP, IMGMAP, and (starting June 1992) OCNMAP. These algorithms have employed both linear and non-linear, split and triple window equations, and different coefficients to account for changing atmospheric parameters. In this section, these algorithms are described along with comparisons of each made with moored mid-lake buoy temperatures.

3.1 SST ALGORITHMS

NESDIS initially used a manually-initiated procedure called SSTMAP to process CoastWatch scenes for the Great Lakes. From April 1990 through June 1991, 729 scenes were processed and received at GLERL. More five-lake scenes were processed than the other higher resolution scenes. The number of scenes processed decreased significantly to one or two images per week during November, December, January, and February when cloud cover limited the amount of useful temperature data that could be retrieved. In May 1991, an automated procedure called IMGMAP was implemented at NESDIS (operational June 1991 to date) to generate Great Lakes CoastWatch imagery. Only NOAA 11 scenes are processed, but all available scenes from each satellite pass are processed. From May 1991 to February 1992, 3179 Great Lakes scenes were processed using IMGMAP equations. In June 1992, a new mapping procedure called OCNMAP and new daytime and nightime SST equations (to better account for atmospheric parameters) will become operational. The major differences between OCNMAP and SSTMAP or IMGMAP algorithms are the use of a nonlinear equation for the nighttime scene and new "atmospheric" coefficients. For more information on SST algorithms see Tadepalli (1990) and Walton et al. (1990).

3.1.1 SSTMAP

For NOAA 11, the multi-channel, linear equations used to calculate surface temperature are (Sapper 1991, personal communication):

Daytime split-window: $SST = 0.9712\,(T4) + 2.0663\,(T4-T5) + 1.8983\,(T4-T5)(\sec\theta - 1) - 1.979\,(\sec\theta - 1) + 8.36$

Nighttime triple-window: $SST + 0.99\,(T4) + 0.9528\,(T3-T5) + 0.6335\,(T3-T5)(\sec\theta - 1) + 0.5215\,(\sec\theta - 1) + 3.93$

where SST is the surface temperature (in degrees Kelvin), T3, T4, and T5 are the calibrated brightness temperatures (in degrees Kelvin) of the 3.7, 11, and 12 μm channels (3, 4, and 5) respectively, and θ is the satellite zenith angle (the angle between the local vertical and a line from the pixel to the satellite). The multi-channel approach attempts to indirectly correct for some of the atmospheric effects inherent in the recorded satellite data. However, the coefficients used in the NOAA-11 equations were derived and validated for over-ocean conditions. For NOAA-10, the channel 4 (10.5-11.5 μm) brightness temperatures were used directly as surface water temperatures for both daytime and nighttime scenes without any attempt to correct for atmospheric effects.

3.1.2 IMGMAP

The algorithms used are the multi-channel SST (MCSST) linear equations developed for global sea surface temperature analysis as described in Pichel et al. (1991). For NOAA 11, the equations are:

Daytime split-window: $SST = 1.02455\,(T4) + 2.4522\,(T4-T5) + 0.6406\,(T4-T5)(\sec\theta - 1) - 7.52$

Nighttime triple-window: $SST = 1.036027\,(T4) + 0.892857\,(T3-T5) + 0.520056\,(T3-T5)(\sec\theta - 1) - 9.224$

3.1.3 OCNMAP

The OCNMAP procedure (operational June 1992) will use two sets of equations for Great Lakes temperature imagery: a linear, split window MCSST equation for the daytime pass and a non-linear, split window NLSST equation for the nighttime pass as given below (Sapper and Pichel 1992, personal communications).

Daytime split-window: $MCSST = 1.02015\ (T4) + 2.320\ (T4\text{-}T5) + .489\ (\sec\theta - 1)\ (T4 - T5) - 278.6$

Nighttime split-window: $NLSST = .95554\ (T4) + .08435\ (Tfld) * (T4\text{-}T5) + 1.1127\ (T4\text{-}T5)\ (\sec\theta - 1) - 259.3$

where SST is in degrees C, Tfld is daytime split-window MCSST, T4 and T5 are channel 4 and channel 5 brightness temperatures in degrees K, and $\sec\theta$ is secant of satellite zenith angle.

3.2 VERIFICATION

Over-lake surface temperatures from all sufficiently cloud-free, manually geo-corrected, synoptic images for the period May 1990 through May 1991 (SSTMAP) and June 1991 through February 1992 were compared with water temperature data recorded by NOAA Data Buoy Center (NDBC) weather buoys. The buoys are deployed in the lakes only during the ice-free season. The buoys provide hourly readings of wind speed, wind direction, air temperature, water temperature, wave height, and wave period. The location of the buoys is shown in Figure 2. The images were manually geo-corrected (shifted) to optimally align shorelines with the fixed graphics overlay for each scene to accurately locate buoy positions. If an image was visually determined to be cloud-free over the area near the buoy, the average surface temperature of the nine pixels nearest the buoy was calculated and compared to the water temperature reported by the buoy (with a hull-mounted thermistor about 0.5 m below the surface) at the time of the satellite overpass.

A total of 971 pairs of temperatures were used for the SSTMAP comparison. The results were analyzed for any systematic differences. The differences found did not depend significantly on wind speed, air temperature, water temperature, air-water temperature differences, or buoy location. There were, however, significant differences between results for NOAA 10 and NOAA 11 satellites and also between NOAA 11 daytime and NOAA 11 nighttime algorithms. It was found that satellite-derived water temperatures are generally cooler than buoy temperatures, with mean differences of about 1 degree C for NOAA 10 and daytime NOAA 11, to 1.7 degrees C for nighttime NOAA 11. Scatter about the mean is significantly lower for the NOAA 11 multi-channel algorithms than for the NOAA 10 channel 4 data (1.17 and 0.79 degrees C for the NOAA 11 daytime and nighttime passes respectively, and 1.42 and 1.56 degrees C for the NOAA 10 passes.) These values are comparable to the 1 degree C accuracy reported for NOAA 2 imagery by Strong (1974) and for Landsat TM thermal data by Lathrop and Lillesand (1987).

For the IMGMAP comparison, a total of 1012 observation pairs were used. Satellite mean temperatures for NOAA 11 daytime and nightime algorithms were almost exactly the same as the buoy mean temperatures. Scatter about the mean is generally significantly less than for either the NOAA 10 or NOAA 11 SSTMAP mappings, and similarly, less for the IMGMAP NOAA 11 nighttime (triple-window) than for the IMGMAP NOAA 11 daytime (split-window). Deviations are comparable to those between monthly mean satellite-derived SST and ship observations reported by McClain et al. (1985). Improvement in IMGMAP temperatures can be attributed to the use of improved "atmospheric" coefficients, the lack of channel 4 brightness temperatures, and the band non-linearity correction applied to the data used in the IMGMAP procedure. Results of the comparisons are shown in Table 3.

Similar comparisons will be made when sufficient data produced by the OCNMAP algorithms are available. However, based on a comparison of temperatures (at NDBC and AES (Atmospheric Environment Service) buoy locations) produced by OCNMAP and IMGMAP equations using a recent daytime and nighttime scene with mid-lake weather buoy temperatures, OCNMAP derived temperatures for both scenes are closer to the buoy temperatures in the majority of cases as shown in Table 4. The use of modified "atmospheric" coefficients and a nonlinear, split-window SST nighttime algorithm in the OCNMAP procedure should further improve the accuracy of the SST product.

4.0 COASTWATCH SYSTEM COMPONENTS

A number of CoastWatch system components and services are shared among the nine current CoastWatch Regional Sites (Beaufort, NC; Ann Arbor, MI; Narragansett, RI; Miami, FL; Bay St. Louis, MS; La Jolla, CA; Seattle, WA; Anchorage, AL; and Honolulu, HI). Communications requirements of CoastWatch are served by the NOAA Ocean Communications Network (NOCN), a system created to serve the communications and data quality enhancement needs of the NOAA ocean community. At GLERL, files are downloaded daily from the NOAA Ocean Products Center (OPC) in Camp Springs, MD via a dedicated high speed line, stored on a computer, and made available to local CoastWatch users over INTERNET or over dial-in telephone lines. At 9600 baud, the 300 k byte image files take approximately 5-10 minutes to download. Over INTERNET (56 k baud), the same file takes about 2-3 minutes to download. Image files for the previous two months are kept online and are available to local CoastWatch participants. After that period, image files are available from an archive at the NOAA Ocean Data Center (NODC). The NOAA Coastal Active Access System (NCAAS) has been developed specifically for the CoastWatch program and serves as the data archive for all Regional Sites served by NOCN.

CoastWatch image files can be displayed and analyzed on computer hardware and software systems of varying capabilities. The minimum system requirements are a 286 or 386 PC with a VGA monitor. In addition to commercially available image processing systems, a number of public domain and shareware software packages are available including two developed by NESDIS specifically for CoastWatch image data. The VGA Image Desktop Analysis System (VIDAS) requires a minimum configuration of a desktop personal computer with a VGA monitor (see Urbanski and Dennis, 1992). Another system, the Interactive Digital Image Display and Analysis System (IDIDAS) requires a proprietary graphics card and a 512x512 color monitor in addition to a PC with VGA monitor. This system has display, shift image (geocorrection), analysis, annotation, and print capabilities and is described by Celone and Tseng (1991).

6.0 SUMMARY

CoastWatch, a program within the NOAA Coastal Ocean Program, is designed to provide near real-time access to satellite imagery, image products, and in situ environmental data for U.S. coastal regions to support Federal and state decision makers and researchers who are responsible for managing the Nation's living marine resources and ecosystems. In 1990, the Great Lakes region became part of the CoastWatch program. The initial CoastWatch product for the Great Lakes was digital imagery of lake surface temperature derived from NOAA AVHRR satellite data and mapped into four 512x512 pixel "scenes" covering the lakes at 1.3 and 2.6 km resolution. During the period April 1990 to February 1992, nearly 4,000 images (from SSTMAP and IMGMAP procedures) of surface water temperature for these four scene areas were processed and received electronically via the NOAA Ocean Communications Network. Comparison of satellite-derived water temperatures with temperatures measured by mid-lake weather buoys shows satellite temperatures an average of about 1 degree C cooler than buoy temperatures with an RMS deviation of 1-1.5 degrees C. The current Great Lakes CoastWatch product suite of surface temperature images, Marine Observation Data, and FIBS gridded wind fields will be enhanced in 1992 by the OCNMAP procedure to include NOAA 11 visible and near-infrared reflectance, brightness temperatures, and solar and satellite zenith angle data. Future CoastWatch products, such as ocean color and ice mapping, are planned based on new satellite sensors such as SeaWifs and Synthetic Aperature Radar.

Acknowledgements: This paper was produced as part of the NOAA Coastal Ocean Program - NOAA CoastWatch. GLERL Contribution Number 808.

7.0 REFERENCES

Bolgrien, D.W. and A.S. Brooks (1992) Analysis of thermal features of Lake Michigan from AVHRR satellite images. J. Great Lakes Res. 18(2):259-266.

Celone, P.J. and W.Y. Tseng (1991) INTERACTIVE DIGITAL IMAGE DISPLAY AND ANALYSIS SYSTEM (IDIDAS) USER'S GUIDE. NOAA Tehnical Report NESDIS 59, National Environmental Satellite, Data, and Information Service, Washington, D.C., pp. 68.

Kidwell, K.B. (ed.) (1991) NOAA Polar Orbiter Data Users Guide (TIROS-N, NOAA-6, NOAA-7, NOAA-8, NOAA-9, NOAA-10, NOAA-11, NOAA-12). National Environmental Satellite, Data and Information Service, National Climatic Data Center, Satellite Data Services Division, Washington, D.C. 20233. pp. 280.

Koczor, R.J. (1987) Multispectral sensing with the AVHRR. ITT Aerospace Optical Division, Fort Wayne, Indiana, 9pp. (presented at the North American NOAA Polar Orbiters Users Group Meeting, Boulder, Colorado, July, 1987).

Lathrop, R.G. and T.M. Lillesand (1987) Calibration of thematic mapper thermal data for water surface temperature mapping: case study on the Great Lakes. Remote Sensing Environ. 22:297-307.

McClain, E.P., W.G. Pichell, and C.C. Walton (1985) Comparative performance of AVHRR-based multichannel sea surface temperatures. J. Geophys. Res. 90(C6):11587-11601.

Pichel, W., M. Weaks, J. Sapper, K. Tadepalli, A. Jandhyala, and S. Ketineni (1991) Satellite mapped imagery for CoastWatch. In Proceedings, 7th Symposium on Coast & Ocean Management, pp.2531-2545. Long Beach, ASCE.

Pyke, T.N. (1989) CoastWatch: New mission for NOAA weather satellites. Sea Technology 30(4):27-32.

Schwab, D.J., G.A. Leshkevich, and G.C. Muhr (1992) Satellite measurements of surface water temperature in the Great Lakes - Great Lakes CoastWatch. J. Great Lakes Res. 18(2):247-258.

Strong, A.E. (1974) Great Lakes temperature maps by satellite (IFYGL). In Proceedings 17th Conf. Great Lakes Res., pp. 321-333. Int. Assoc Great Lakes Res.

Tadepalli, K. (1990) User's Manual for the NOAA-K, L, and M Environmental Image Products, SM Systems and Research Corporation, Landover, Maryland (prepared for NOAA/NESDIS under contract No. 52-DDNE-9-00018), 90 pp.

Urbanski, J. and R. Dennis (1992) VIDAS NOTES FOR USERS. National Environmental Satellite, Data, and Information Service, Office of Research and Applications, Washington, D.C., pp. 59.

Walton, C.C., E.P. McClain, and J.F. Sapper (1990) Recent changes in satellite-based multi-channel sea surface temperature algorithms. Preprint, MTS90, Marine Technology Society, Washington, D.C.

Table 1. Daily OCNMAP Image Product Suite (June 1992)

Window	Product Type Image File Extension	Description
Great Lakes Synoptic	LC1	Channel 1 Reflectance
	LC2	Channel 2 Reflectance
	LC3	Channel 3 Brightness Temperatures
	LC4	Channel 4 Brightness Temperatures
	LC5	Channel 5 Brightness Temperatures
	LD1	Daytime Split-Window MCSST
	LS3	Nighttime Split-Window NLSST
	LZS	Satellite Zenith Angle
	LZA	Solar Zenith Angle
Lake Superior	SC1	Channel 1 Reflectance
	SC2	Channel 2 Reflectance
	SD1	Daytime Split-Window MCSST
	SS3	Nighttime Split-Window NLSST
	SZA	Solar Zenith Angle
Lake Michigan/Huron	MC2	Channel 2 Reflectance
	MD1	Daytime Split-Window MCSST
	MS3	Nighttime Split-Window NLSST
	MZA	Solar Zenith Angle
Lake Erie/Ontario	EC1	Channel 1 Reflectance
	EC2	Channel 2 Reflectance
	ED1	Daytime Split-Window MCSST
	ES3	Nighttime Split-Window NLSST
	EZA	Solar Zenith Angle

Table 2. CoastWatch Windows for the Great Lakes

	Latitude Range (N)	Longitude Range (W)	Pixel Size (km) (at mid-latitude)
Full Region	38.89 - 50.58	75.88 - 92.41	2.56
Superior	43.59 - 49.28	84.19 - 92.45	1.24
Michigan-Huron	40.76 - 46.73	79.78 - 88.05	1.30
Erie-Ontario	40.76 - 46.73	75.88 - 84.16	1.30

Table 3. Comparison of AVHRR SST With NDBC Buoy SST

	Observation Pairs	Buoy Mean	Satellite Mean	Mean Offset	RMS Deviation
SSTMAP NOAA-10 day	171	9.67	8.63	1.05	1.42
SSTMAP NOAA-10 night	281	11.32	10.27	1.05	1.56
SSTMAP NOAA-11 day	315	11.00	9.88	1.13	1.17
SSTMAP NOAA-11 night	204	10.24	8.53	1.72	0.79
IMGMAP NOAA-11 day	501	15.70	15.81	-0.11	1.05
IMGMAP NOAA-11 night	511	15.74	15.76	-0.03	0.83

Table 4. Surface Water Temperatures (C) at Buoy Locations

CoastWatch image: G9214919.LD1 Date: 5-28-92

	NDBC buoy locations								AES buoy locations					
Source	45001	45002	45003	45004	45005	45006	45007	45008	45132	45134	45135	45136	45137	45139
IMGMAP	2.24	2.71	1.76	3.06	13.65	0.94	5.65	2.47	10.00	10.5	4.82	-	2.00	17.06
BUOY	2.78	3.89	3.33	2.78	13.89	2.78	7.22	4.44	10.00	11.67	6.11	3.33	4.44	12.22
MCSST B	3.06	3.76	2.71	2.59	14.24	1.29	6.59	3.41	11.18	11.76	5.18	-	3.88	24.12

CoastWatch image: G9216209.LS3 Date: 6-10-92

	NDBC buoy locations								AES buoy locations					
Source	45001	45002	45003	45004	45005	45006	45007	45008	45132	45134	45135	45136	45137	45139
IMGMAP	1.88	7.65	2.71	1.41	15.29	0.00	10.82	7.18	14.12	13.65	8.00	2.47	5.29	10.59
BUOY	2.78	11.11	3.33	2.78	16.11	2.78	11.11	8.33	13.33	15.28	10.00	3.33	8.33	13.33
OCNMAP B	3.41	8.71	3.41	2.12	14.94	1.18	10.00	7.41	13.65	13.65	8.24	3.06	5.65	8.35

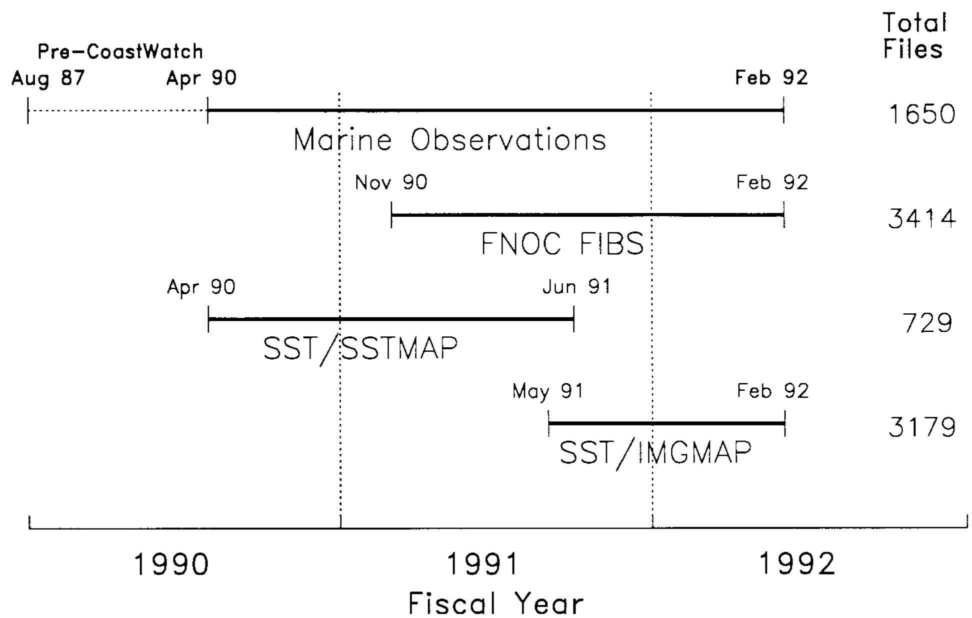

Figure 1. Great Lakes CoastWatch Products 1990-1992.

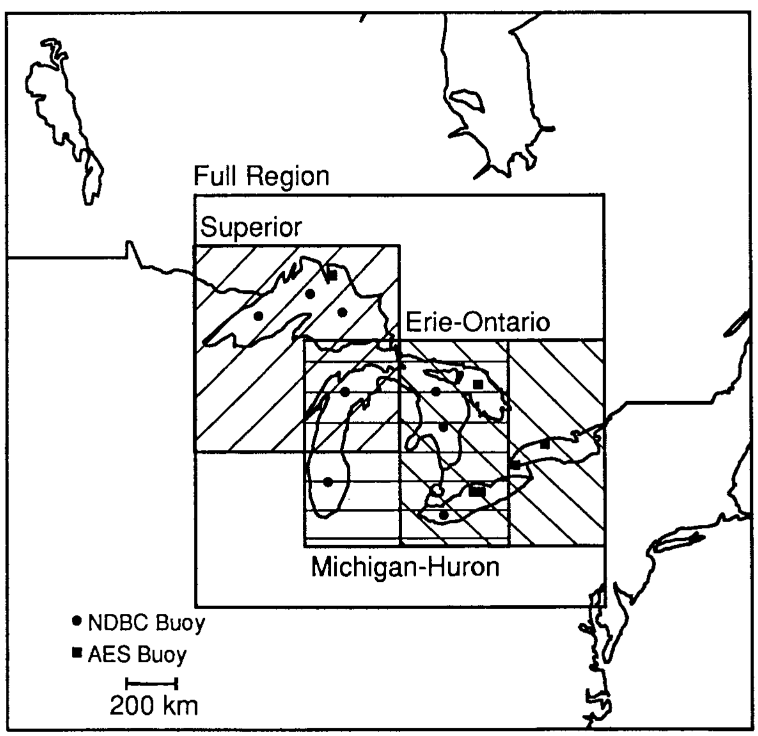

Figure 2. Great Lakes CoastWatch Scenes.

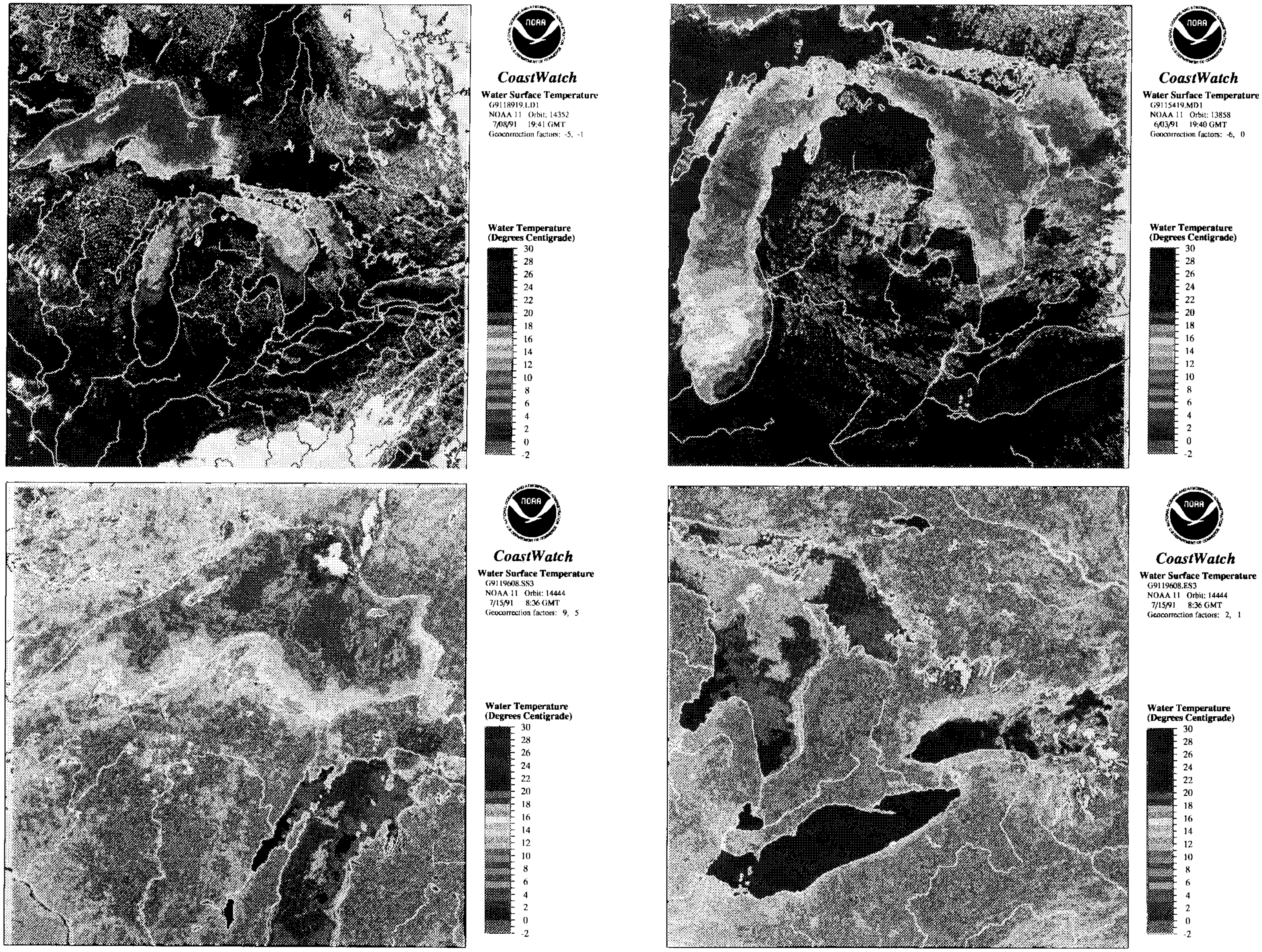

Figure 3. Surface Temperature Images for Each of the Four Great Lakes CoastWatch Scenes.

Figure 4. NOAA-11 AVHRR Visible (Channel 1) Image (L. Michigan/Huron) 19 May 1992.

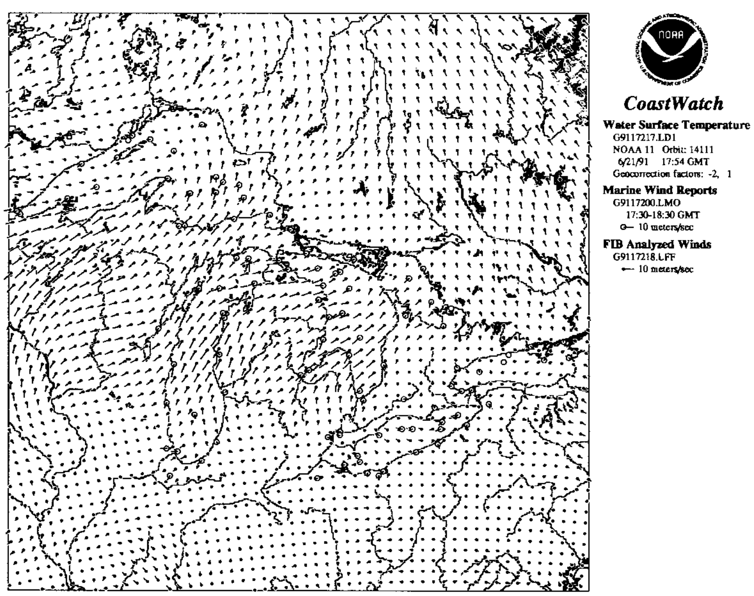

Figure 5. FIBS Modeled Wind Field for 21 June 1991 (17:30 - 18:30 GMT),
Plotted at 30 Km Grid Resolution.